

## R & D for Future ZEPLIN

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We propose a new concept for a very low background multi-ton liquid xenon Dark Matter experiment. The detector consists of two concentric spheres and a charge readout device in the centre. Xenon between the two spheres forms a self-shield and veto device. The inner surface of the central sphere is coated with CsI to form an internal photocathode with minimum of  $2\pi$  coverage for any event in the active volume. Photoelectrons from the CsI photocathode drift toward the charge readout micro-structure in the centre of the detector. Both scintillation and ionisation are measured simultaneously for background rejection and 3-D event mapping. In addition to external shielding, the low background is achieved by eliminating PMTs and by using low radioactivity pure materials throughout the detector. We present detailed calculations of the charge readout system and design details. The detector is expected to probe the full SUSY parameter space.

### 1. Introduction

Liquid xenon is a promising target material for direct WIMP detection experiments, due to its relatively high density of  $3 \text{ g/cm}^3$ , allowing greater sensitivities to be reached with lower volumes. Additionally, it has excellent ionisation and scintillation properties [1]. Experimental programs that use liquid xenon as a target medium are currently being pursued by the ZEPLIN [2], DAMA [3], XMASS [4] and XENON [5] Collaborations. To reach even greater sensitivities than those proposed by the above experiments, a large target mass and materials with a low intrinsic radioactive background

need to be used. For efficient scintillation light collection a multi-tonne detector would require a significant number of photomultipliers to cover the large target surface. Compared to other sources of radioactivity, such as  $^{85}\text{Kr}$  concentrations in xenon and ultra-pure copper, low background PMTs still contribute significantly to the background, and hence affect the sensitivity of the detector [6]. An attractive alternative to PMTs is the CsI photocathode coupled with a segmented charge amplifying and readout device. The low cost, flexible readout configuration and relatively low intrinsic background of these devices with respect to PMTs makes research in this area essential for the next generation of dark matter detectors. Additionally, the use of liquid

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xenon as an active veto surrounding the main target, means that fewer materials are required to separate the two regions and  $4\pi$  coverage can be attained. In this paper the feasibility of such a detector is discussed.

## 2. Spherical Detector Principles and Operation

A 10 cm radius ball that is covered with a charge collecting and amplifying readout microstructure is located at the centre of the detector. The LXe target with a mass of 1.3 T, is encased within a 1 cm thick electroformed, high-purity copper shell with a radius of 50 cm. The inner surface of this shell is coated with CsI, acting as the photocathode. The self-shield and veto consists of a sphere of liquid xenon surrounding this copper shell, extending to a radius of 81 cm from the centre of the detector. The entire structure is insulated within a copper vacuum jacket. Field shaping rings are mounted on insulator PTFE, which is attached to a copper cylinder extending from the vacuum jacket to the central ball. The signal is readout from anodes at ground. An additional electrode of the microstructure is kept at negative potential, decoupling the drift and amplification regions. This creates in a very short distance a very high electric field for charge amplification in liquid.

An interaction in the target causes a simultaneous creation of scintillation light and ionisation charge. The negative potential of the central sphere with respect to the inner ball results in the radial drifting of electrons toward the centre of the detector, where the amplification and signal readout take place. With highly segmented readout, ionisation electrons due to short range of radiation tracks would produce a signal in a small number of readout channels (primary pulse). In contrast, photons from scintillation are emitted isotropically, converted into photoelectrons from CsI with a quantum efficiency of 30% [7]. These would produce a signal in a larger number of readout channels (secondary pulse). Hence the signal from charge and light can be additionally to its sequence better distinguished. The time between these two pulses multiplied by the electron drift

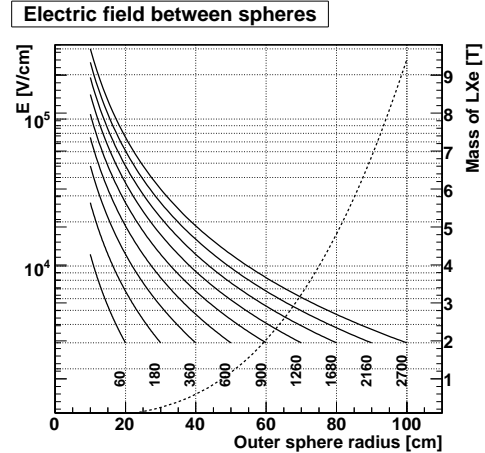


Figure 1. Electric Field between Spheres assuming that radius of inner ball is 10 cm. For an outer sphere radius of 50 cm, a potential difference of 600 kV between the outer sphere and inner ball is required in order to maintain an electric field strength greater than 3 kV/cm across the target. The field at the surface of the inner ball is 75 kV/cm. The active target mass is approximately 1.3 T.

velocity gives the radial coordinate information of the event. Other two coordinates are delivered from the position of the fired readout channels. It is essential that the electrons drift at the same velocity, irrespective of the non-uniform field across the liquid. However, as shown in figure 1, the spherical detector operates with a non-uniform field where  $E \propto \frac{1}{r}$ . The drift velocity of electrons in liquid xenon saturates at 3 kV/cm [8], hence for a central ball and photocathode of radius 10 and 50 cm, respectively, a potential difference of 600 kV is required to create a minimum field in the chamber of 3 kV/cm at the photocathode, as shown in figure 1. Additionally the quantum efficiency of the CsI gets higher in strong electric fields [7].

## 3. Charge Readout and Signal Feedback Problem

Good light collection is essential for detection of the secondary pulse. Because light is converted

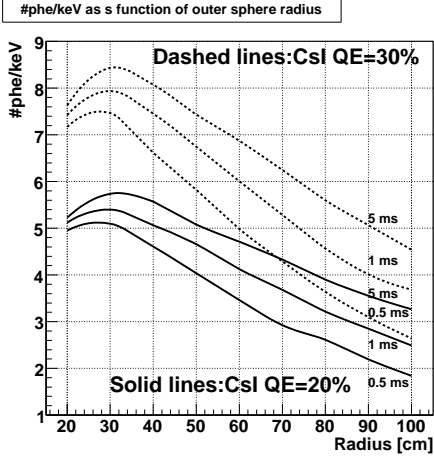


Figure 2. Results from Monte Carlo Calculations of the Number of Photoelectrons/keV as a Function of the Outer Sphere Radius. Electron lifetime values of 0.5, 1 and 5 ms are shown, for CsI QE=20 and 30%. With an outer sphere of radius 50 cm, a light collection efficiency varies between 4 and 7.5 photoelectrons/keV.

into photoelectrons it depends on the purity of the xenon, the attenuation length of light (100 cm in liquid xenon [9]) and the quantum efficiency of the CsI. The purity of liquid xenon is often quoted with reference to the lifetime of electrons passing through it. Results from Monte Carlo calculations, shown in figure 2, indicate that a light collection efficiency of 4 to 7.5 photoelectrons/keV is expected for an outer sphere radius of 50 cm. A threshold electric field strength of 1 MV/cm [1] is required for avalanche development, and hence charge amplification in liquid xenon. Maximum gains of 100 [10] and 400 [11] have been observed in liquid xenon. However, proportional scintillation light is created in electric fields greater than 400 to 700 kV/cm [12], causing after-pulses and leading to discharge. Other problems include local imperfections of the readout surface, causing very high electric fields, and the slow motion of avalanche ions, thus building space charge. Additionally, the level of maximum gain increases with the purity of xenon. There are two types of possible charge readout devices that have the poten-

tial to operate at such high electric field strengths with small differential voltage: cold field emission devices; and micropattern detectors. Cold field emission devices have already been used in liquid argon, but no gain was seen due to bubble formation on the sharp edges of the readout electrode, hence creating a conduction path and discharges [13]. These devices have not been tested in liquid xenon, and if the formation of bubbles can be halted, then their use becomes an attractive alternative. Conventional charge readout devices, such as Micromegas and Microstrip Gas Chamber (MSGC) can also be used. A gain of 10 has already been observed with MSGCs in liquid xenon [14].

As discussed earlier, a non-ending cycle of after-pulses are seen due to the threshold electric field strength for avalanche development being greater than that for proportional scintillation light creation in liquid xenon. A high electric field local to the charge readout device is essential for high gain, as is a 100%  $4\pi$  charge collection efficiency. One possible solution is to use a high-voltage switch [15], such that when the potential of the cathode is 0 V, the maximum electric field strength local to the charge readout device drops below 100 kV/cm preventing from proportional light creation in LXe. Another possible solution is to use a light blocking focusing-defocusing device allowing electrons to travel through to the inner ball [16].

#### 4. Shielding

An attractive feature of the detector geometry is the self-shielding provided by a 30 cm thick layer of liquid xenon that constitutes the outer sphere. There is the possibility of placing a charge readout device outside this layer, hence making this an active veto. Gamma-background simulations were performed with GEANT4 [17], for  $^{238}\text{U}$  and  $^{232}\text{Th}$  content in the sphere holding this xenon shield. A concentration of 0.05 ppm was assumed, which is the same as that in current dark matter detectors. Over 30 cm, the number of interactions/day dropped by over 2 orders of magnitude. Approximately  $0.504 \pm 0.081$  and  $0.525 \pm 0.084$  events/day for interactions from  $^{238}\text{U}$  and

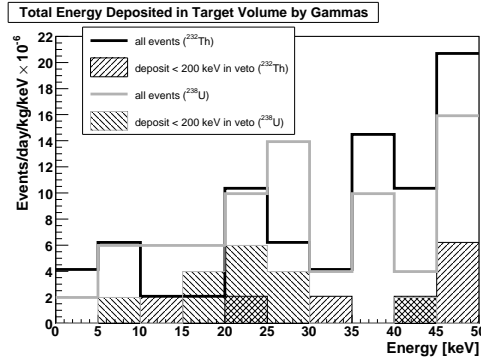


Figure 3. Total Energy Deposited in Target Volume by Gammas from  $^{238}\text{U}$  and  $^{232}\text{Th}$ . The intensity drops from  $0.504 \pm 0.081$  to  $0.525 \pm 0.084$  events/day and  $0.116 \pm 0.039$  to  $0.094 \pm 0.034$  events/day for gamma-rays from  $^{238}\text{U}$  and  $^{232}\text{Th}$  respectively if an active liquid xenon veto is employed.

$^{232}\text{Th}$  gamma-rays respectively was determined, as shown in figure 3. Assuming that with an active veto, gamma-rays that deposit greater than 200 keV in the shielding can be excluded, the respective intensities drop to  $0.116 \pm 0.039$  and  $0.094 \pm 0.034$  events/day, also shown in figure 3. Therefore, the veto provides a very good shield against external gamma-ray sources.

## 5. Plans for R & D Program

Future plans include: the study of the scintillation properties of liquid xenon at high electric fields (such as the scintillation light and charge yield), the determination of an accurate value of the electric field threshold for proportional light creation and maximum charge multiplication in LXe using micro-structure devices.

## 6. Summary

The concept of a new spherical detector geometry using charge readout devices coupled with CsI photocathode has been presented. Greater sensitivities can be reached with this detector than with current dark matter search experiments due to the large target mass, high efficiency of

the scintillation light collection, low radioactive background materials used in its composition and the self-shielding properties of a 30 cm liquid xenon veto with  $4\pi$  coverage. The development of charge readout devices in liquid xenon is still in its infancy, and further research and development is required in this area in order to realise this detector.

## REFERENCES

1. T. Doke, Nucl. Instrum. Methods 196 (1982) 87
2. G.J. Alner et al., New Astron. Rev. 49 (2005) 259;
3. R. Bernabei et al., Nucl. Instrum. Methods Phys. Res. A 482 (2002) 728
4. S. Moriyama, in: N.J.C. Spooner (Ed.), V. Kudryavtsev (Ed.), Proc. 5th Int. Workshop on the Identification of Dark Matter, 2004, p. 248
5. E. Aprile et al., New Astron. Rev. 49 (2005) 289
6. M.J. Carson et al., Nucl. Instrum. Methods Phys. Res. A 548 (2005) 418
7. E. Aprile et al., Nucl. Instrum. Methods Phys. Res. A 343 (1994) 129
8. L.S. Miller, S. Howe, W.E. Spear, Phys. Rev. 166 (1968) 871
9. A. Baldini et al., Nucl. Instrum. Methods Phys. Res. A 545 (2005) 753
10. M. Miyajima et al., Nucl. Instrum. Methods 134 (1976) 403
11. S.E. Derenzo et al., Phys. Rev. A 9 (1974) 2582
12. K. Masuda et al., Nucl. Instrum. Methods 160 (1979) 247
13. J.G. Kim et al., Nucl. Instrum. Methods Phys. Res. A 534 (2004) 376
14. A.P.L. Policarpo et al., Nucl. Instrum. Methods Phys. Res. A 365 (1995) 568
15. E. Aprile et al., in: IEEE International Conference on Dielectric Liquids, 2005, p. 345
16. M. Atac et al., New Astron. Rev. 49 (2005) 283
17. S. Agostinelli et al. (2006), <http://geant4.web.cern.ch/geant4/>